THE PHI-METER: A FUEL-INDEPENDENT INSTRUMENT FOR MONITORING COMBUSTION EQUIVALENCE RATIO

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Gaseous carbon monoxide is mainly responsible for deaths due to unwanted fires[1]. This has been a major difficulty to specialists in fire protection engineering, since quantitative methods for predicting CO yields from building fires have not been available. Recent studies have indicated that the production of CO is primarily controlled by the equivalence ratio, φ, which is defined as

$$\phi = \frac{[fuel/oxygen]}{[fuel/oxygen]_{stoic}}$$

where 'stoich' denotes the stoichiometric fuel/oxygen ratio; it represents the actual fuel/oxygen ratio, compared to its stoichiometric value. Thus, $\varphi < 1$ implies fuel-lean and $\varphi > 1$ implies fuel-rich combustion.

Studies by Toner et al.[2] on methane, Morehart et al.[3] on methane and ethylene, and Beyler [4],[5] on hydrocarbons, alcohols, as well as several polymers indicate an abrupt increase in the CO concentration by more than a factor of 10 as the global equivalence ratio increases from about 0.5 to 2. By 'global,' we mean here the overall equivalence ratio for the combustion process and not any spatial variations of fuel or oxygen concentrations. These studies were steady state and involved the collection of the products of combustion in a hood. Under such circumstance the global equivalence ratio were obtained from GC measurements in the studies by Toner and Morehart and by the use of several real time gas analyzers by Beyler. Gas Chromatography is less useful for full scale enclosure fires for realistic fuels because of the presence of soot and a wide range of unburned hydrocarbons and because of both spatial and temporal variations in the species concentrations. Here we describe a device with a single gas analyzer that is able to monitor the local equivalence ratio during a large scale test.

The measuring principle is related to the Oxygen Consumption Method, which has been used to sense indirectly the heat released from combustion processes[6],[7],[8]. The basic concept is that the combustion products are sampled into a combustor to burn all of the carbon atoms in the fuel to CO_2 and all of the hydrogen atoms in the fuel to H_2O. The combination of 1000°C chamber temperature, the platinum catalyst, and the approximately 10 s residence time insures that the smoke and other gaseous products of incomplete combustion are converted to CO_2 and H_2O. The CO_2 and H_2O are scrubbed from the exhaust so that only O_2 and N_2 enter the oxygen analyzer.

With this method, the oxygen concentration is measured: (a) for the ambient air without oxygen addition ($X^o_{O_2}$), (b) for ambient air with oxygen addition ($X^i_{O_2}$), and (c) for the sampled combustion products with oxygen addition (X_{O_2}). Analysis of these measurements then yields φ through the following equation:

$$\varphi = \frac{X^i_{O_2} - X_{O_2}}{X^o_{O_2}(1 - X_{O_2})} .$$

From the equation it is seen that there is a simple relationship between the measured exhaust concentration of oxygen and the equivalence ratio. Furthermore the result is independent of the fuel type.

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The performance of the phi-meter has been evaluated by comparing the instrument results with the metered flow rate of fuel and air. Comparisons have been made for a variety of gases including methane, acetylene, and budadiene. The estimated uncertainty for the phi-meter is on the order of $\pm 3\%$ of full scale. The instrument response time is about 60 s and the measurement range extends from $\phi=0.1$ to at least $\phi=3$. The phi-meter has been successfully used with both reduced scale and full scale enclosure fires. The latest version of the phi-meter includes a microprocessor with a direct output reading in terms of equivalence ratio.

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